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STATUS REPORT OF RESEARCH

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AND-CONTROL

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Prepared by

Michael Athans  
Robert R. Tenney  
Alexander H. Levis  
Elizabeth R. Ducot

Submitted to: Dr. Charles Holland  
Code 411MA, Room 607  
Office of Naval Research  
800 North Quincy St.  
Arlington, VA, 22217

MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
LABORATORY FOR INFORMATION AND DECISION SYSTEMS  
CAMBRIDGE, MASSACHUSETTS 02139

### Summary

This document contains an informal status report of the research activities of faculty, staff, and students affiliated with the M.I.T. Laboratory for Information and Decision Systems on distributed estimation, communication, and decision problems motivated by tactical C<sup>3</sup> issues.

The research described herein was supported in whole or in part by contract ONR/N00014-77-C-0532 (NR 041-519 and NR 277-300x). The contract monitors were Drs. Stuart L. Brodsky and Charles Holland of the Office of Naval Research. The reporting period covers the time-period 1 September 1981 to 1 September 1982.

### The Expert Team of Experts Conceptual Model

The complexity of the human  $C^2$  decision processes and of the hardware/software of the  $C^3$  system cannot be examined independently. Some sort of a philosophical point of view has to be taken, and a general methodology has to be adopted, so as to guide the necessary basic relevant theoretical investigations in the area of distributed  $C^2$  decision problems.

Prof. Athans has adopted a normative/descriptive approach to  $C^2$  organizations. Each warfare commander is viewed as an expert in his warfare area; his tactical decisions are modeled as the outcome of a constrained optimization problem that reflects his human limitations, i.e., short-term memory limitations. This point of view is then reflected as a principal model of the mission environment, warfare mission objectives, and tactical information unique to each expert warfare commander.

However, such a normative model of a warfare commander is a necessary, but by no means sufficient, subelement to a model of a  $C^2$  organization operating under a coordinated distributed command doctrine (such as the Naval CWC doctrine for battle group defense operations). It is argued that, as a consequence of joint operations planning and tactical team-training, each expert warfare commander augments his own principal model by a set of mutual models; each mutual model represents an aggregated version of the other commanders principal model. The development of these mutual models is the result of team-training and results in an expert team of experts.

It is hoped that the above framework will form the basis for mathematical formulations that address organizational issues and distributed decision issues. A very preliminary set of working examples related to ship

positioning for combined AAW and ASW operations is being developed by Ms Magonet-Neray and Prof. Athans.

#### Documentation

The following paper will be published in the Fall 1982 issue of the IEEE Control Systems Magazine

- M. Athans, "The Expert Team of Experts Approach to  $C^2$  Organizations" LIDS-P-1166, MIT, November 1981.

Additional near-term documentation will be provided in the S.M. thesis of Ms. Magonet-Neray scheduled for completion in December 1982, and subsequent publications based upon the thesis.

#### Distributed Decision Theory

The long-range goal of this research is to establish a rigorous mathematical framework for developing fundamental limitations upon distributed decision processes as compared to centralized ones.

In the past year Prof. Athans and Mr. Tsitsiklis have developed a set of theorems which prove asymptotic agreement by a set of  $M$  agents, with common prior information and common objective function, but different real-time information. In the absence of communications, each agent will generate a different (tentative) optimal decision in view of the assumed differences in the available data. However, if the agents communicate to each other their tentative optimal decisions, and each agent updates his optimal decision based upon the other agents' decisions received by him, then asymptotically all agents will converge to a common decision (which may be different than the centralized one).

Future research will address additional mechanisms, e.g. different prior information, that will contribute to further mechanisms that cause the agents to arrive at different decisions; and to define communication/coordination mechanisms that lead to a set of satisficing solutions.

#### Documentation

An oral presentation of the above results was presented by Prof. Athans at the 5th MIT/ONR Workshop on  $C^3$  systems.

The following paper has been distributed, accepted for publication in the Proceedings of the IEEE Conference on Decision and Control, Orlando, FLA, December 1982, and is currently being reviewed for the IEEE Trans. on Automatic Control.

J.N. Tsitsiklis and M. Athans, "Convergence and Asymptotic Agreement in Distributed Decision Problems," LIDS-P-1185, MIT, March 1982 (Revised July 1982).

#### Problems of Organizational Structure in $C^3$ Systems

The objective of this research by Dr. Levis and Mr. Boettcher is to model the elements of organizations, especially naval organizations, consisting of human decision-makers supported by  $C^3$  systems. In previous work a model of a human decisionmaker executing well defined decisionmaking tasks was introduced. Decisionmaking was modeled as a process which consists of a situation assessment stage, a response selection stage, and interactions with other decisionmakers. An information theoretic mathematical framework has been used in which total internal activity for each

decisionmaker is described in terms of internal coordination, internal information generation, information transmission and blockage. Bounded rationality, an expression of the information processing limitations of a human decisionmaker, has been modeled as a constraint of the total information processing activity; the bound depends on the rate of information processing and on the tempo of operations.

Work under this task has been focused on the analysis of teams of decisionmakers that have to carry out a well defined task. Direct control by one decisionmaker over another has been modeled as a restriction on the response selection stage of the second decisionmaker through command inputs from the first. Indirect control has been modeled as a result-sharing activity; results from the situation assessment stage of each decisionmaker are shared with others. The use of both direct and indirect control mechanisms allows the modeling of a wide range of relationships between team members and, consequently, of a wide variety of organizational structures.

The significant accomplishment to date has been the extension of the theory to small teams of decisionmakers that can be represented by acyclical information structures.

#### Documentation

- A.H. Levis and K.L. Boettcher, "On Modeling Teams of Interacting Decisionmakers with Bounded Rationality," LIDS-P-1189, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, March 1982. To appear in the Proc. of IFAC/IFIP/IFORS/IEA Conf. on Analysis, Design and Evaluation of Man-Machine Systems, Pergamon Press, September 1982.

### Information Structures for Single Echelon Organizations

A methodology for designing the information structures for decision makers who comprise the boundary between an organization and its environment has been developed by Dr. Levis and Ms. Stabile. The environment has been modeled as a source that generates symbols or messages that the organization members must process without being overloaded. Two basic information reduction strategies have been considered: (1) creation of self contained tasks, and (2) creation of slack resources. The former has led to the partitioning of the input signal and the parallel processing of the partitions; the latter to alternate processing where each decision maker receives signals according to some deterministic or stochastic rule, but is given more time to process then, i.e., a delay is introduced. These two strategies were integrated to produce a variety of information structures for special cases.

This project has been completed. Further activity is planned when the procedures for designing multi-echelon organizations are developed.

### Documentation

- D.A. Stabile, "The Design of Information Structures: Basic Allocation Strategies for Organization," S.M. Thesis, Report LIDS-TH-1098, Lab. for Inf. and Decision Systems, MIT, Cambridge, MA, June 1981.
- D.A. Stabile, A.H. Levis, S.A. Hall, "Information Structures for Single Echelon Organizations; Paper LIDS-P-1180, Lab. for Inf. and Decision Systems, MIT, Cambridge, MA, June 1982.

### Effectiveness Analysis of C<sup>3</sup> Systems

A methodology for analyzing and assessing the effectiveness of command, control and communications systems is being developed by Dr. Levis and Mr. Bouthonnier. The analysis is carried out by characterizing in terms

of attributes the  $C^3$  system and the missions it supports. These attributes are determined as functions of primitives that describe the system, the mission and the context within which both operate. Then the system capabilities and the mission requirements are compared in a common attribute space. This comparison leads to the evaluation of partial measures of effectiveness which are then combined to yield a global measure. The methodology has been applied to the assessment of the effectiveness of a simple communications network operating in a hostile environment. Further work is planned in developing further the methodology and in applying to other types of  $C^3$  systems.

#### Documentation

V. Bouthonnier, "System Effectiveness Analysis for Command and Control," S.M. Thesis, Report LIDS-TH-1231, Lab. for Inf. and Decision Systems, MIT, September 1982.

V. Bouthonnier and A.H. Levis, "Effectiveness Analysis of  $C^3$  Systems," Paper LIDS-P- , Lab. for Inf. and Dec. Systems, MIT, Cambridge, MA, September 1982. To appear in Proc. 5th MIT/ONR Workshop on  $C^3$  Systems, Monterey, CA, August 1982.

#### Optimal Decentralized Control of Finite Nondeterministic Systems

A formal problem involving multiple decision agents cooperatively seeking to optimize the performance of a dynamic system has been posed and solved by Prof. Tenney. Despite different information available to each agent, and the attendant second guessing and signalling problems, interesting exact solutions emerge. This is due to the use of a minmax,



nondeterministic formulation rather than an expected value, stochastic one; the minmax criterion facilitates the construction of manageable sufficient statistics for each agent by merging several past observation histories which need not be distinguished.

The results of this effort provide one case of a distributed decision problem which can be solved, and thus interesting insights into the nature of exact, optimal solutions which can perhaps be generalized to more complex systems.

#### Documentation

None as yet

#### Distributed Decision Structures

This research deals with investigation of problem formulations which employ realistic models of  $C^3$  decision structures. This project seeks to identify those aspects of distributed decision making which are different in reality and theory, and pose new theoretical problems which capture the realistic aspects. Thus far, attention has focussed on identification of issues, including:

- limited knowledge of system external to agents
- clear lines of authority, responsibility, and monitoring activity
- unclear modes of interaction between agents
- loci of open loop vs. closed loop decisionmaking.

The next phase will involve problem formulations, solutions to which will stimulate new theoretical insights.

Documentation

- R.R. Tenney, "The Role of Distributed Knowledge in Distributed Decisionmaking," Large Scale Systems Symposium, Virginia Beach, Oct. 1982.

Many-on-Many Air Defense Intercept Strategies

Issues related to multiple AEGIS cruiser and destroyer coordination, to successfully carry the AAW function in both battle groups and battle forces against a very dense coordinated air attack, provide numerous opportunities for examining distributed tactical decision strategies.

During the past year Prof. Athans and Mr. Chow have initiated a study that explicitly takes into account the AEGIS reflecting radar illumination time constraints within the context of the traditional shoot-look-shoot (SLS) interception strategies and a novel shoot-look-reassign (SLR) strategy. The SLR strategy assumes that missiles, already launched, can be reassigned to different targets following the time-instants of kill-assessments. Survival probabilities have been calculated using the SLS and SLR strategies against a class of very dense attacks and some numerical results have been obtained, which indicate the superiority of the SLR strategy in some simple scenarios.

Further research is needed to assess the performance of the two strategies. A very unconventional stochastic dynamic programming optimization problem must be formulated and solved before any definitive conclusions can be drawn.

Documentation

An oral progress report on the above research topic was presented by Prof. Athans at the 5th MIT/ONR workshop on  $C^3$  systems. Additional near-term documentation will be contained in the S.M. thesis by Chow scheduled for completion in November 1982.

### Issues in Distributed Surveillance

Some of the qualitative issues involved in the design of a distributed, multiobject surveillance system were explored by Prof. Tenney and Mr. Salmon. Attention was focussed on the low signal to noise ratio, high clutter situation. A number of issues were analyzed, not for exact algorithm design, but to establish some qualitative performance tradeoffs. Conclusions involving communication strategies, target handoff, and data fusion were drawn. The results of this effort are motivating subsequent work by L. Ng on exact algorithm design.

### Documentation

- W.P. Salmon, "Multiobject Tracking in Distributed Sensor Networks," S.M. thesis, MIT, October 1981.

### Distributed Communication and Detection Problems

The problem of designing the decision rules for individual nodes in a fixed network of sensors and bandlimited communication links, where the objective is to test several (static) underlying hypotheses, has been solved by Prof. Tenney and Mr. Ekchian. The solution comes in two ways:

- a) for specific, simple examples, exact expressions have been found which give the (finite number of) parameters needed to specify the decision rules, and
- b) a general approach to any network has been found. This approach exploits the underlying causality induced by the communication links to produce a dynamic programming-like algorithm for finding decision rules. Generality is achieved at the cost of dimensionality, so it is expected that only small numbers of hypotheses and communication symbols per link can be handled.

Moreover, a number of interesting examples have been developed which illuminate some of the design issues related to structuring the communication network in the first place.

#### Documentation

- L.K. Ekchian, R.R. Tenney, "Detection Networks," 21st CDC, Orlando, FLA, 1982.
- L.K. Ekchian, R.R. Tenney, "Detection Networks, IEEE Transactions on Automatic Control, to appear.
- L.K. Ekchian, "Optimal Design of Distributed Detection Networks," Ph.D. Thesis, to appear Oct. 1982.
- L.K. Ekchian, R.R. Tenney, "Detection Networks," MIT/ONR C<sup>3</sup> Workshop, August 1982.

#### Optimal Sensor Scheduling

This research carried out by Prof. Tenney deals with a derivation of an optimal algorithm for tasking sensors so to test multiple hypotheses given noisy observations. An elegant algorithm emerges from a problem formulation which seeks to optimize a criterion based on the posterior probability distribution on the hypotheses. By choosing a cost structure which has eigenfunction properties with respect to the update operation, a closed form analytic solution may be obtained. Interesting insights into geometric measures of information, as well as easily implementable solutions to some search and identification problems, are obtained.

#### Documentation

- R.R. Tenney, "Optimal Sensor Scheduling for Multiple Hypothesis Testing," LIDS Report, Oct. 1981, also 5th MIT/ONR C<sup>3</sup> Workshop, Aug. 1982.

#### Distributed Estimation in Communication Networks with Delay

Classical formulations of estimation problems assume instantaneous communication from sensors to estimators. Formulations of decentralized optimal estimation problems result in strong incentives for the system to use the communications capacity available to the greatest extent possible. In practice, this is not optimal; increased traffic leads to networks congestion and decreased performance. This effort by Prof. Tenney and Mr. Ozbek is aimed at investigating the tradeoffs involved in determining sensor reporting schedules: long periods between reports leads to low traffic and hence low communication delay, but result in poor use of sensor information, while short periods lead to long delay but nearly complete information. A number of example problems have been solved exactly; work is continuing on a general approach.

#### Documentation

- None as yet; Mr. Ozbek's S.M. thesis is scheduled for completion in Spring 1983.

#### Algorithms for Distributed State Estimation

Existing theory for decentralized estimation yields a number of special cases, including the LQG case, but extension to the general case is not trivial. When the state dynamics are discrete, for example, the only exact

formulation involves (static) hypothesis testing on the discrete state trajectories. This effort by Prof. Tenney and Mr. L. Ng is aimed at developing algorithms for achieving this estimation optimally while reducing the computational burden. Criteria for locally rejecting a hypothesis, even without communication with other sites, have already been found. Introducing communication remains to be done. It is probably not entirely coincidental that both distributed, discrete state estimation and centralized, hybrid state estimation both force one to consider state trajectories, rather than just the current state, if optimum use of information is to be made.

#### Documentation

This effort is just starting; no publications are available yet. Mr. Ng's S.M. thesis will be completed in the Spring of 1983.

#### Hybrid State Estimation

A formulation of the hybrid (combined discrete and continuous) state estimation problem has been developed by Prof. Tenney and Mr. Bruneau which leads to an optimal solution structure paralleling many of the ad hoc solutions existing in the literature. This provides a framework for analyzing and extending the performance of these algorithms. Structurally, the algorithm seeks to find the Maximum A Posteriori (MAP) estimate of the combined discrete/continuous state trajectory, and finds pruning rules for the set of discrete trajectories which mirror the Viterbi algorithm. The continuous trajectories are handled parametrically by a Kalman filter variation (in the linear Gaussian case).

The formulation is a natural one for unifying the approaches taken to tracking a maneuvering target in bursty clutter. Extensions to the multi-target case have been pursued, but there seems to be some additional structure available which has not yet been introduced to the theory, and which is needed to further reduce computation. This structure includes (a) the union operation describing the detections of multiple targets, and (b) the possibility of discrete hypothesis merging.

#### Documentation

The research was documented as follows:

- F. Bruneau, "An Approach to Hybrid State Estimation with Applications to Multiobject Tracking," Thesis, January 1982.

Also Prof. Tenney, presented an oral progress report at the 5th MIT/ONR C<sup>3</sup> Workshop.

#### Optimal Location of Distributed Data Bases in a Vulnerable Communication Network

The long-range goal of this research is to develop new theoretical and algorithmic results for the generic problem of storing the appropriate number of copies of important files at suitable computer nodes in a vulnerable military radio data communication network. The vulnerability of the nodes and links of the communication network is modeled via their survival probabilities, and reflect a hostile environmental tactical environment (node destruction, link jamming etc.).

The optimal file location problem was not considered in the literature for the case of vulnerable data communication networks. In the past year Prof. Athans and Mr. Ma have developed the appropriate theorems to handle a wide class of redundant file location problems. Also, computer algorithms were developed and

numerical results were obtained for several networks (up to 10 nodes). The numerical problem involves the solution of a constrained nonlinear integer programming problem.

Future research will be directed toward a more realistic modeling of the  $C^3$  environment in our general theoretical/algorithmic framework. In particular, sensor and data fusion nodes will be included. Furthermore, we shall investigate the generic problem of improving the quality of the  $C^2$  decision processes (modeled by the probability that a particular commander or a team of commanders can access the information contained in a particular file and its redundant copies) as a function of improvements in the physical components of the data communication network (less costly file storage, jam-resistant links, etc.).

#### Documentation

Prof. Athans presented an oral progress report on this topic at the 5th MIT/ONR workshop on  $C^3$  systems. A technical paper documenting the results to date will become available in October 1982 and will be submitted for publication.

#### TECCNET

TECCNET (Testbed for Evaluating Command and Control Networks) is a small, expandable software system created at MIT by Ms. Ducot to support  $C^3$  system research. It has been designed to highlight the complex interactions between the distributed command and control network elements, the algorithms and



procedures that characterize the information flow network and the environment within which the systems function. The intent is to provide a consistent framework for both model development and experimentation that will permit us to integrate many of the partial results obtained thus far by members of the MIT C<sup>3</sup> project team.

Activities this year have been focused on developing an implementation plan for the augmented TECCNET system. Particular areas of interest that have received the greatest attention thus far are the following:

1) Conversion of TECCNET to a multi-user system. The conversational interface has been expanded to meet the needs of users with different levels of software and system expertise. On-line help and documentation facilities have been added, as were as the support software for generating and catalogering scenarios.

2) The characteristics of the models, likely to be developed in the near future, have been identified. The effects of these characteristic have been incorporated in the expanded event generator.

3) Baseline modeling environments, including distributed network management tools, have been implemented. These baselines will permit experiment with the distributed detection techniques to be formulated, and, beginning in the fall, to be implemented and carried out.

#### Documentation

An oral progress report was presented by Ms. Ducot at the 5th MIT/ONR workshop on C<sup>3</sup> systems; a paper for the workshop proceedings is currently under preparation.

### Query Optimization in Distributed Databases

Distributed database management systems (DDBMS) are amongst the most important and successful software developments in this decade. They are enabling the computing power and data to be placed within the user environment close to the point of user activities. The performance efficiency of DDBMS is deeply related to the query processing strategies involving data transmission over different nodes through the network. This research studied the optimization of query processing strategies in a distributed databases environment.

With the objective of minimum communication costs, Prof. Davenport and Mr. Huang have developed a mathematical model to find a join-semijoin program for processing a given equi-join query in distributed homogeneous relational databases. Rules for estimating the size of the derived relation are developed. The parameters for estimating the size of derived relation form a consistent parameter system. The distributed query processing problem is formulated as a dynamic network problem. We have also extended this model to consider both communication cost and local processing cost. For a simpler case where all semijoin reducibilities are zero, we have shown that under three different objective functions, the problems of finding a routing strategy of required data to the site where a query is initiated are NP-complete. We analyzed the difficult nature of the query processing problem and provide an analytical basis for heuristic algorithms.

We have extended this model to query processing in a distributed heterogeneous databases environment. A heterogeneous database communication system is proposed to integrate heterogeneous database management systems to

combine and share information. The use of a database communication system for heterogeneous DBMSs makes the overall system transparent to users from an operational point of view. Problems of schema translation and query translation of the query processing in this environment were studied.

#### Documentation

The research output will be shortly documented in the following doctoral thesis scheduled for completion in October 1982.

- Kuan-Tsae Huang, "Query Optimization in Distributed Data Bases," Ph.D. Thesis, MIT, Dept. of Electrical Engineering and Computer Sciences, October 1982.

Also several papers are planned following the thesis publication.